Applied Energy 164 (2016) 211–219

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Design optimisation for window size, orientation, and wall reflectance with regard to various daylight metrics and lighting energy demand: A case study of buildings in the tropics

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HIGHLIGHTS

- Influence of WWR, wall reflectance, and window orientation on daylight metrics in the tropics.
- A simple multi-objective optimisation approach was proposed by pairing the results.
- Optimum solutions in all Pareto frontiers were filtered against the criteria and were ranked.
- Three optimum solutions were found, all with south window orientation.
- The approach enables to observe inter-relationship between the performance indicators.

ARTICLE INFO

Article history:
Received 30 July 2015
Received in revised form 6 November 2015
Accepted 28 November 2015
Available online 21 December 2015

Keywords:
Window-to-wall ratio
Wall reflectance
Façade orientation
Daylight metrics
Lighting energy demand
Optimisation

ABSTRACT

Design optimisation problems of window size and façade orientation in buildings have been investigated many times, with regard to energy and comfort criteria. To indicate daylight availability in indoor spaces, a number of daylight metrics have been proposed, but those metrics are not always fully accounted in the optimisation process. Also, most studies were conducted for locations with high latitude, where the sun is located most of the time either at the south or at the north part of the sky hemisphere, which is not the case in the tropics. Therefore, this article presents a simulation study to investigate the influence of window-to-wall ratio (WWR), wall reflectance, and window orientation on various daylight metrics and lighting energy demand in simple buildings located in the tropical climate. A simple approach for the multi-objective optimisation was proposed by classifying the results in six pairs of two different performance indicators. Solutions in all Pareto frontiers were filtered against the defined target criteria, and were accepted into the optimum solution space if they belong to at least 4 out of 6 Pareto frontiers, and were ranked either in the order of their mean distance to the utopia points, or in the order of number of times they belong to a Pareto frontier. Three optimum solutions are found, all of which belong to four Pareto frontiers. The most optimum solution with the least mean distance to the utopia points is the combination of WWR 30%, wall reflectance of 0.8, and south orientation. The proposed approach enables one to observe the inter-relationship between the involved performance indicators, while providing a possibility to visualise the boundaries of the solution space.

1. Introduction

Windows are regarded as one of the most important building components, and are acknowledged for their positive influence on the health and well-being of building occupants. Moreover, windows play an important role not only in providing daylight and view [1–4], but also in shaping the overall energy demand in buildings [5–10]. In the design phase, contradictions often occur when trying to maximise daylight penetration and view, which usually translates to applying large windows, while trying to minimise energy consumption, which usually translates to applying small windows.

The problems can be even more complex, knowing that perception of comfort is heavily dependent on numerous aspects and parameters, which can also have a conflicting nature among themselves. These conflicting objectives commonly require a multi-objective optimisation approach [11–14].

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http://dx.doi.org/10.1016/j.apenergy.2015.11.046
0306-2619/

The investigation to find the optimum window configuration and its impact on the energy performance of the building has been conducted by many researchers since long time ago (e.g. [15–17]). An optimum window-to-wall ratio (WWR) is believed to be able in yielding significant energy savings for heating, cooling and lighting demand in buildings. Later on, the influence of the material of the fenestration [18–20] and the integration of active elements such as photovoltaic panels [21–27] has been investigated as well. Over the broad and extensive results, it is noticed that as more efficient technologies are employed in buildings, the influence of WWR on the building energy performance tends to become lower [28].

However, several issues in the topic of WWR study are yet to be addressed. Two of them are the use of appropriate metrics for indicating daylight performance in the interior spaces, and the specific application for buildings in tropical region. These two issues are discussed in this article.

1.1. Daylight metrics

In some of the aforementioned references, artificial lighting energy consumption was not evaluated. Meanwhile, it is realised that integration and better use of daylight is important in achieving energy savings [29], and the optimisation of window size should consider both energy consumption and visual acceptance criteria [30].

To indicate the availability of daylight in interior spaces, a number of metrics have been proposed, ranging from the established daylight factor (DF) [31,32], to the emerging climate-based daylight metrics such as the daylight autonomy (DA) [33] and useful daylight illuminance (UDI) [34,35]. The DF is now seen as a 'static' metric, since it is insensitive to climate variation. The DA and UDI are 'dynamic' in a sense that they take into account the variation of sky conditions over the year, which highly depends on the local climate type. Moreover, both DA and UDI respectively also require a defined minimum and a range of acceptable illuminance values.

Nevertheless, not all of those daylight metrics are accounted in the optimisation process, i.e. researchers normally choose a metric that is considered more suitable to indicate the daylighting performance, rather than evaluate all metrics and observe their inter-relationship. Some researchers prefer using DA (e.g. [30,36]) as daylighting performance indicator, since most national standards prescribe minimum (rather than a range of minimum and maximum) illuminance values for task-specific activities. Some prefer using UDI (e.g. [37,38]), considering the risk of visual discomfort, which is normally characterised with an upper threshold of illuminance or luminance values. There are also a few researchers who prefer using only daylight uniformity ratios (e.g. [39]).

While the choice of using UDI seems fair and efficient for the optimisation purpose, the investigation of Reinhart et al. [40,41], which links the perception of daylit areas according to building occupants and simulations of daylight metrics, has shown that the DA can better predict the perceived daylight condition in interior spaces, as compared to other daylight metrics. This suggests further investigation on the particular topic of choosing the most appropriate daylight metrics, which for now is still very much an open-ended question. Having known that, it is therefore necessary to include DA and UDI, as well as DF and uniformity ratios in the optimisation process, to observe their inter-relationship and how they are affected by the input variables.

1.2. Daylighting in tropics

Secondly, it is noticed that most studies on window optimisation were conducted for locations with high latitude (beyond 23.5°N and 23.5°S), particularly North America and Europe (e.g. [20,28,30,36–38]). In those regions, the sun's apparent position is mostly at the south part of the sky hemisphere, since the geographical locations are in the northern hemisphere, giving an intuitive knowledge on which façade orientation receiving the most sunlight.

In the tropical region, particularly in locations nearby the equator (approximately in latitudes 10°N–10°S), for a part of the year, the sun's apparent position is slightly at the north part of the sky hemisphere, while for the rest of the year it is at the south part of the sky. Sunshine duration is relatively longer than that in the non-tropical climates. Seasonal variation is low, but the presence of wet and dry seasons, referring to periods with high and low precipitation, is observed. The context is therefore somewhat unique and different, compared to cases in high latitude regions.

Review and analysis of daylighting systems for buildings in the tropics are available [42–46], so are information on solar radiation, sky luminance, and other related data for the tropics [47–51]. Few studies on the influence of building envelopes on ventilation and thermal comfort in Singapore and Indonesia [52,53] and on incident solar radiation in Malaysia [54] are also available. Lifetime performance of innovative technologies such like semi-transparent building integrated PV systems in Singapore has been discussed [55]. Nevertheless, in general, window optimisation studies dedicated for locations in the tropics are still relatively rare, and therefore can be further explored.

1.3. Aim and objectives

The aim of this study is to demonstrate the importance of daylight criteria consideration in optimising the design of window size, orientation, and wall reflectance. A large number of daylight metrics have been proposed by many researchers, but these metrics are not always fully accounted in the optimisation process. Meanwhile, these various metrics can also interact with each other, in a sense that the inter-relationship between them should be also observed and understood.

The objectives are to obtain the most influential design parameters, for which sensitivity analysis was performed; and to find the most optimum solutions, for which a simple approach is proposed by ranking the solutions on the Pareto frontiers that satisfy the defined criteria. For the case study, a location in the tropical region is chosen, since most studies on window optimisation were conducted for locations with high latitude. The context of tropical regions is somewhat unique and different compared to cases in high latitude regions.

Section 2.1 describes the relevant settings of simulation that was employed to generate the results. Section 2.2 describes the assessment method by giving the performance indicators, sensitivity analysis, and multi-objective optimisation procedure. The results are given and discussed in Section 3, while Section 4 presents the conclusion of the article.

2. Method

2.1. Settings

The space observed in this study is an office room, based on the IEA Task 27 reference office [56], having internal dimensions of L 5.4 m × W 3.5 m × H 2.7 m (Fig. 1). Reflectance values of the ceiling and the floor were respectively 0.85 and 0.20, according to the IEA Task 27. The window was assumed to consist of a single glazing with typical visible transmittance of 0.88. No shadings, furniture, and other accessories were associated with the space. The workplane area is divided into two zones of equal size. In the centre of each zone, a calculation point is defined.

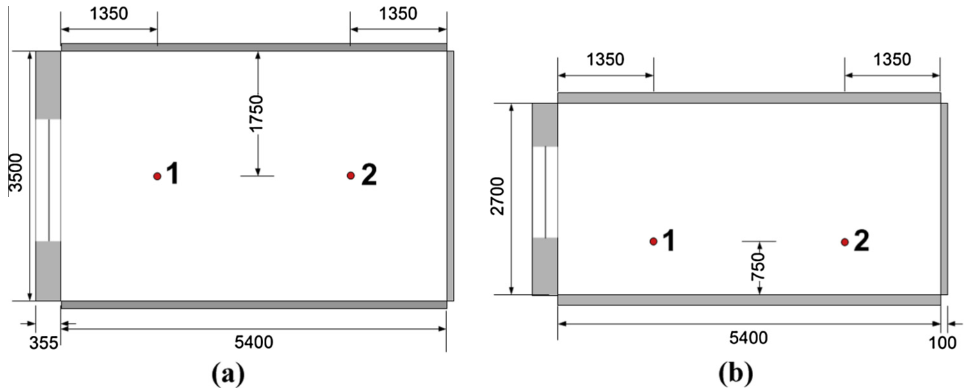

Fig. 1. (a) Plan view and (b) section view of the simulated space.

The WWR was varied from 30% to 80% in an interval of 10%, as shown in Fig. 2. The minimum 30% WWR was taken to ensure that view to the outside is sufficiently available, while the maximum 80% WWR was taken to reasonably limit the negative impact of excessive solar penetration in the forms of heat and glare.

While the reflectance of ceiling and floor was kept constant, the reflectance of walls was varied from 0.4 to 0.8 in an interval of 0.1, in order to incorporate the contribution of internally reflected component (IRC) of daylight to the workplane illuminance [57–59]. In addition, four major orientations of the window were tested as well.

The model geometry was created in *Radiance* [60], and was later imported to *Daysim* [61] to perform the annual daylighting analysis, using a grid resolution of 0.5 m and a time step of 5 min. The simulation parameters in *Daysim* are set as shown in Table 1. The space was assumed occupied on Mondays until Fridays, from 08.00 to 17.00 h local time. Artificial lighting was installed with total power of 200 (=4 × 50) W, corresponding to a lighting power density of 10.58 W/m^2. Lighting control of "combination on/off occupancy and dimming system" was applied, with occupancy sensor delay time of 5 min. The user behaviour for lighting use was assumed to be a mixture of both active and passive.

The site location was set for Bandung, Indonesia (6.93°S, 107.61°E), which is located in the Af (tropical rainforest) climate region according to Köppen–Geiger climate classification. The city is located at an elevation of around 750 m above sea level, lying on a river basin surrounded by volcanic mountains. Due to its elevation, the climate is cooler than most Indonesian cities and is classified as humid; the average temperature is 23.6 °C throughout the year. The average annual rainfall ranges from 1000 mm to 3500 mm. The wet season is around November–April, while the dry season is expected in the rest of the year, conforming to most other Indonesian regions.

The local weather data file in ∗.epw format was provided by the Institute of Research and Development for Dwellings, the Ministry of Public Work and Housing of the Republic of Indonesia.

Table 1
Daysim simulation parameters.

Parameter	Value
Ambient bounces (ab)	5
Ambient divisions (ad)	1000
Ambient super-samples (as)	20
Ambient resolution (ar)	300
Ambient accuracy (aa)	0.1
Limit reflection (lr)	6
Specular threshold (st)	0.15
Specular jitter (sj)	1
Limit weight (lw)	0.004
Direct jitter (dj)	0
Direct sampling (ds)	0.2
Direct relay (dr)	2
Direct pretest density (dp)	512

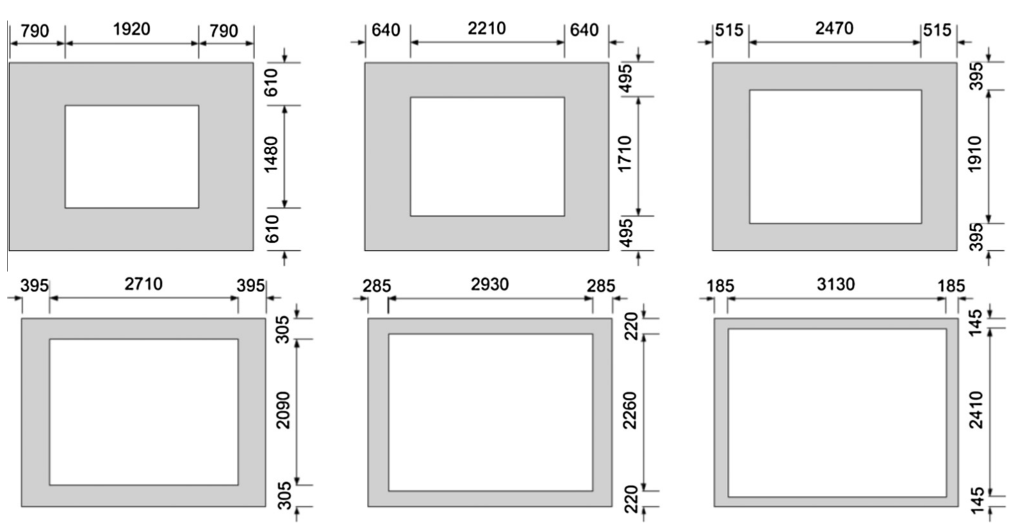

Fig. 2. Elevation view of the window wall, with WWR of 30%, 40%, 50%, 60%, 70%, and 80%.

2.2. Assessment

2.2.1. Performance indicators

The performance of the observed spaces in this study is assessed with a number of indicators (hence performance indicators), which are considered relevant with the focus of the study, i.e. related to daylight availability and electrical lighting energy demand in indoor spaces. In total, six performance indicators were chosen and defined as follows:

(1) *Average daylight factor* (DF_{av}), i.e. the average of DF at Points 1 and 2. DF itself is the ratio between the illuminance at an interior horizontal point to the illuminance at an unshaded, horizontal exterior point. In general, an average DF value of 2% is recommended for typical office activities [62]. Therefore, DF_{av} is to be maximised with minimum criterion of 2%.

(2) *Average uniformity* (U_{av}), i.e. the annual average of ratio between illuminance at Point 2 (farther to the window) and that at Point 1. There exist many criteria for uniformity under both daylighting and artificial lighting scenes [62–65]. In this study, considering higher tolerance of contrast under daylighting scene, the average uniformity value is targeted at 0.20 (i.e. a ratio of 1:5 [63]). Therefore, U_{av} is to be maximised with the minimum criterion of 0.20.

(3) *Daylight autonomy 300 lx at Point 2* ($DA_{300lx\ (2)}$), i.e. the percentage of occupied times in the year during which a minimum, task-specific illuminance (300 lx in this case) can be met by daylight alone at Point 2, which is closer to the back of the room. The Illuminating Engineering Society (IES) recommends a target illuminance 300 lx for typical offices, classrooms, and library, and a minimum DA of 50% of the occupied times of the year [33]. Therefore, $DA_{300lx\ (2)}$ is to be maximised with the minimum criterion of 50%.

(4) *Useful daylight illuminance 100–2000 lx at Point 1* ($UDI_{100-2000lx\ (1)}$), i.e. the percentage of occupied times in the year during which a certain range of illuminance (100–2000 lx in this case) can be met by daylight alone at Point 1, which is closer to the window. Point 1 was selected instead of Point 2, since the risk of exceeding the maximum value of 2000 lx is higher in Point 1, and thus needs to be controlled. $UDI_{100-2000lx\ (1)}$ is to be maximised with the minimum criterion of 50%.

(5) *Simplified daylight glare probability >0.35 at Point 1* ($DGPs_{>0.35\ (1)}$), i.e. the percentage of occupied times in the year during which the simplified daylight glare probability (DGPs) at Point 1 exceeds 0.35. The reason of choosing Point 1 instead of Point 2 is similar with that in the bullet no. (4), however Point 1 for DGPs is assumed at a height of 1.20 m above the floor, corresponding with the typical eye level when sitting. The original concept of DGP was introduced in [66] and validated in [67]. This index is expressed as follows:

$$DGP = 5.87 \times 10^{-5}\ E_v + 0.0918\ \log\left[1 + \sum_{i=1}^{n}\left(\frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}\right)\right] + 0.16 \quad (1)$$

where Ev is the vertical eye illuminance produced by the light source [lx]; L_S the luminance of the source [cd/m^2]; ω_s the solid angle of the source seen by an observer [sr]; and P is the position index, which expresses the change in experienced discomfort glare relative to the angular displacement of the source from the observer's line of sight.

Since calculating DGP for an annual basis requires a high effort to generate images at every time step of the simulations, which is computationally expensive, Wienold [68,69] proposed a simplified version of DGP where the logarithmic term depending on the luminance and solid angle of the source seen from the observation point is neglected.

$$DGPs = 6.22 \times 10^{-5}\ E_v + 0.184 \quad (2)$$

It should be noted that DGPs however cannot be used for absolute glare factor conditions that include a direct view of glare sources in the field of view of the observer [70]. Suggestion for DGP categories has been provided [69]. In general, any DGP value below 0.35 corresponds to 'imperceptible' glare sensation, between 0.35 and 0.40 is 'perceptible', between 0.40 and 0.45 is 'disturbing', while higher than 0.45 is 'intolerable'. Even though DGPs is not capable to entirely represent the actual DGP, it has been conceptually proven that DGPs has a correlation with UDI [71]. In this study, high values of $DGPs_{>0.35}$ is assumed to correspond not only with perceptible glare, which leads to possible visual discomfort, but also with high energy demand for cooling, which for the sake of simplicity is not calculated separately. $DGPs_{>0.35\ (1)}$ is to be minimised with the maximum criterion of 50%.

(6) *Total annual lighting energy demand* (E_L), i.e. the total demand for electrical lighting energy in a year, in kWh/m^2. E_L is to be minimised with no maximum criterion.

2.2.2. Sensitivity analysis

Sensitivity analysis using multiple linear regressions was performed to evaluate the effect of the input variables on the output variables, i.e. the performance indicators, assuming a linear relationship between any output variable y_i and the p-vector of any input variables x_i. This relationship is modelled through an error variable ε_i, which is an unobserved random variable between the output and input variables. The mathematical model reads as follows:

$$y_1 = \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + \varepsilon_i, \quad i = 1, 2, \ldots, n \quad (3)$$

where β_i is a p-dimensional regression coefficient. In this case: $p = 3$, $n = 6 \times 5 \times 4 = 120$, x_{i1} is the WWR, x_{i2} is the wall reflectance, and x_{i3} is the window orientation (given in degrees; North is 0°, East is 90°, and so forth); while y is evaluated for DF_{av}, U_{av}, $DA_{300lx\ (2)}$, $UDI_{100-2000lx\ (1)}$, $DGPs_{>0.35\ (1)}$, and E_L, individually. Since the variables have different units, the values for each of the output and input variables should be standardised, that is:

$$y'_i = \frac{y_i - \bar{y}}{\sigma_y}; \quad x'_{ni} = \frac{x_{ni} - \bar{x}_n}{\sigma_{x_n}} \quad (4)$$

where y'_i and x'_{ni} are the standardised output and input variables, y_i and x_{ni} are the actual output and input variables, $\bar{y}$ and $\bar{x}_n$ are the arithmetic mean of the output and input variables, and σ_y and σ_{x_n} are the standard deviation of the output and input variables. The standardised values are put in the regression model, which reads as follows:

$$\begin{bmatrix} y'_1 \\ \ldots \\ y'_n \end{bmatrix} \begin{bmatrix} x'_{11} & x'_{12} & x'_{13} \\ \ldots & \ldots & \ldots \\ x'_{n1} & x'_{n2} & x'_{n3} \end{bmatrix} \begin{bmatrix} \beta'_1 \\ \beta'_2 \\ \beta'_3 \end{bmatrix} + \begin{bmatrix} \varepsilon'_1 \\ \ldots \\ \varepsilon'_n \end{bmatrix}, \quad i = 1, 2, \ldots, 120 \quad (5)$$

Eq. (5) are then solved to determine β'_1, β'_2, and β'_3, which are the standard regression coefficients (SRCs) that determine the sensitivity of the output as function of the input. An SRC value of 1 corresponds to a high, positive influence of the input, while –1 corresponds to a high, negative influence of the input.

2.2.3. Multi-objective optimisation

Referring to the defined criteria of the performance indicators in Section 2.2.1, the optimisation problem can be formulated as follows:

$$\min \quad E_L \tag{6}$$
$$\text{subject to} \quad \mathrm{DF}_{av} \geqslant 2\% \tag{7}$$
$$U_{av} \geqslant 0.2 \tag{8}$$
$$\mathrm{DA}_{300\mathrm{lx}(2)} \geqslant 50\% \tag{9}$$
$$\mathrm{UDI}_{100-2000\mathrm{lx}(1)} \geqslant 50\% \tag{10}$$
$$\mathrm{DGPs}_{>0.35(1)} \leqslant 50\% \tag{11}$$

A simple graphical optimisation method [30], with some additional rules to filter the solutions, was applied to indicate how these daylight metrics interact with each other, as it is the most direct way to observe the inter-relationship between the selected metrics. The application of evolutionary algorithms such as genetic algorithm and particle-swarm model is indeed effective for searching global optimum, but the interaction between the various involved metrics may not be clearly visible in the search result. Using a graphical optimisation method, this interaction can be easily observed by the design team and the stakeholders.

To find the optimum solutions, all of the obtained results were grouped by pairing two different performance indicators that have a conflicting trend and therefore require a trade-off. Six pairs of performance indicators were selected: E_L vs $\mathrm{DGPs}_{>0.35\ (1)}$, DF_{av} vs $\mathrm{DGPs}_{>0.35\ (1)}$, $\mathrm{DA}_{300\mathrm{lx}\ (2)}$ vs $\mathrm{DGPs}_{>0.35\ (1)}$, U_{av} vs $\mathrm{UDI}_{100-2000\mathrm{lx}\ (1)}$, E_L vs $\mathrm{UDI}_{100-2000\mathrm{lx}\ (1)}$, and DF_{av} vs $\mathrm{UDI}_{100-2000\mathrm{lx}\ (1)}$. The following algorithms were then applied:

(1) The Pareto frontiers, i.e. the non-dominated solutions in all pairs, were sorted out and filtered by applying the relevant optimisation criteria in Eqs. (7)–(11).
(2) The filtered Pareto frontiers in all pairs were sorted out and were accepted into the optimum solution space if they belong to the Pareto frontier in at least 4 (out of 6) pairs of performance indicators.
(3) The optimum solutions were sorted out and ranked in two ways: (1) in the order of their mean distance to the utopia points, or (2) in the order of number of times they belong to a Pareto frontier. Using the second way, if there are more than one solution belonging to a Pareto frontier in the same number of times, then priority is given to the solution with the least distance to the utopia point. The optimum solutions are those which belong to most Pareto frontiers, or those which have the least mean distance to the utopia points.

A utopia point is formally defined as follows: A point f^o is called the utopia point if $f_i^o = \min\{f_i(x)|x \in S\}$, $i = 1, 2, 3, \ldots, k$, where k is the number of the objective functions to be minimised [72]. The utopia point is obtained by minimising each objective function without regard to other objective functions. It is generally unusual to have each minimisation ended up at the same point in the design space, i.e. one design point cannot simultaneously minimise all of the objective functions. The utopia point therefore exists only in the criterion space, and in general is not attainable [72].

The distance to the utopia point was calculated in percent. Therefore, performance indicators that are not given in percent should be first normalised. This applies to total annual lighting energy E_L demand by taking the percentage ratio of the obtained value to the maximum possible value, i.e. the energy demand when the lighting is turned on continuously at 100% power, at all occupied time ($E_{L\max}$, in kW h/m^2). For uniformity, the value is multiplied by 100, to present the value in percent.

The distance to the utopia point in each pair is defined based on the nature of the performance indicators, depending on whether the indicator is to be minimised or maximised. For example, in the pair of E_L vs $\mathrm{DGPs}_{>0.35\ (1)}$, in which both variables should be minimised (i.e. having 0 as the utopia point), the distance $d(E_L$ vs $\mathrm{DGPs}_{>0.35\ (1)})$ is expressed as:

$$d(E_L \text{ vs } \mathrm{DGPs}_{>0.35(1)}) = \sqrt{(E_{Ln})^2 + (\mathrm{DGPs}_{>0.35(1)})^2} \tag{12}$$

where

$$E_{Ln} = \frac{E_L}{E_{L\max}} \times 100\ [\%] \tag{13}$$

Another example, in the pair of U_{av} vs $\mathrm{UDI}_{100-2000\mathrm{lx}\ (1)}$, in which both variables should be maximised, i.e. having 100% as the utopia point, the distance $d(U_{av}$ vs $\mathrm{UDI}_{100-2000\mathrm{lx}\ (1)})$ is expressed as:

$$d(U_{av}\,\text{vs}\,\mathrm{UDI}_{100-2000\mathrm{lx}(1)}) = \sqrt{(100 - 100U_{av})^2 + (100 - \mathrm{UDI}_{100-2000\mathrm{lx}(1)})^2} \tag{14}$$

For any optimum solution fulfilling all requirements in algorithms (1) until (3), the mean distance to the utopia points d_{av} is defined as the average of the distances to the utopia points d_i in all pairs where the solution belongs to the Pareto frontier.

$$d_{av} = \frac{1}{N}\sum_{i=1}^{N} d_i \tag{15}$$

where N is the number of times the solution belongs to a Pareto frontier, which should be $\geqslant 4$ according to algorithm (2).

3. Results and discussion

3.1. Sensitivity analysis

The standard regression coefficient (SRC) of all input variables, evaluated for the six performance indicators, is displayed in Fig. 3. It is observed that WWR is highly influential on almost all performance indicators except the uniformity, which is greatly influenced by wall reflectance (SRC = 0.75). Window orientation is the least influential input variable, it only moderately influences the $\mathrm{DGPs}_{>0.35\ (1)}$ with an SRC of 0.36. However, the $\mathrm{DGPs}_{>0.35\ (1)}$ is not highly influenced by WWR either, as the SRC is only 0.38. This is because the $\mathrm{DGP}_{>0.35\ (1)}$ is considerably higher for east or west orientation, compared to north or south one; even though the average $\mathrm{DGP}_{>0.35\ (1)}$ for all orientations are higher (with large deviations) when the WWR is larger, as shown in Fig. 4. Both WWR and

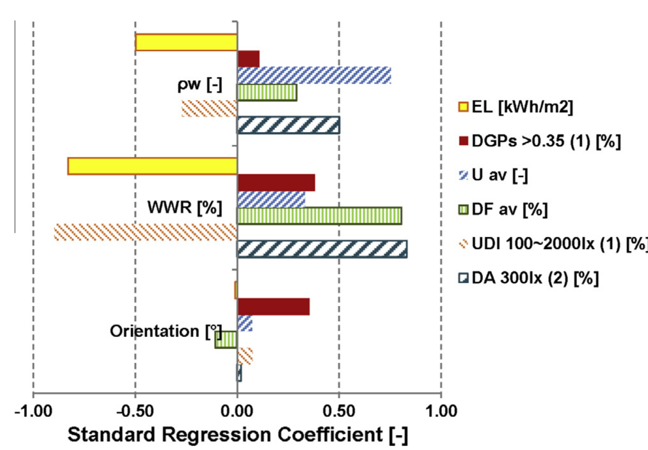

Fig. 3. Standard regression coefficient of the three input variables.

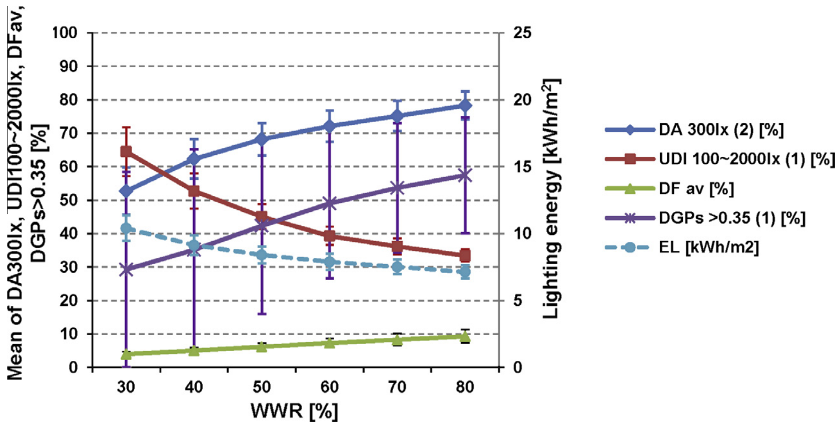

Fig. 4. Relationship between WWR and the mean values of DA_{300lx}, $UDI_{100-2000lx}$, DF_{av}, $DGPs_{>0.35}$, and E_L. Error bars represents standard deviations.

window orientation should be therefore considered equally important in the attempt to achieve acceptable values of $DGPs_{>0.35}$.

To visualise the relationship between the most influential input variables and the influenced performance indicators, Figs. 4 and 5 are drawn, in which the performance indicators are shown as mean values, with error bars indicating the standard deviations.

Fig. 4 clearly shows that as the WWR increases, the daylight metrics with no maximum criteria, in this case DA_{300lx} and DF_{av}, also increase as more daylight is penetrated into the space. Meanwhile, $UDI_{100-2000lx}$ decreases and $DGPs_{>0.35}$ increases as more daylight (or sunlight) of higher than 2000 lx enters the workplane, indicating more risk of having glare and overheating. The total annual lighting energy demand E_L naturally decreases at larger WWR. However, if E_L is added with the likely increasing cooling energy demand at larger WWR, which is indicated by the rising $DGPs_{>0.35}$, the overall total energy demand potentially becomes higher as well. Note that the exact amount of cooling energy demand is not calculated in this study, as the intention is to find the tendency of relationship between relevant variables by using a simplified approach, rather than to determine the actual value of the total energy demand.

The trend lines of E_L and $DGPs_{>0.35}$ crosses each other somewhere around the WWR of 40%, indicating the point in which the minimum total energy demand is achieved. This tendency is also observed in other studies in temperate-oceanic climates [28,30].

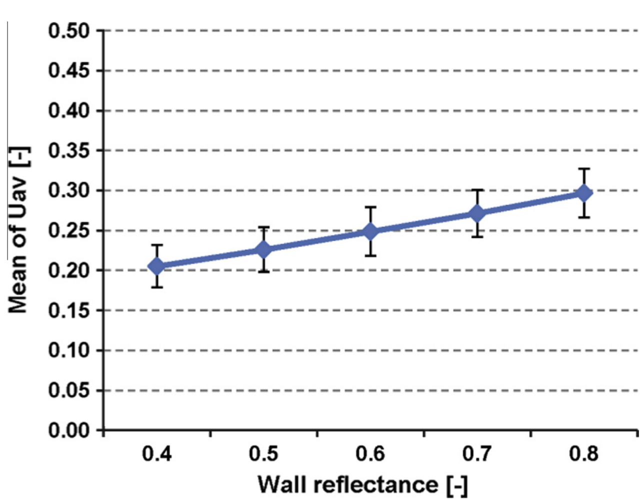

Fig. 5. Relationship between wall reflectance and the mean values of U_{av}. Error bars represents standard deviations.

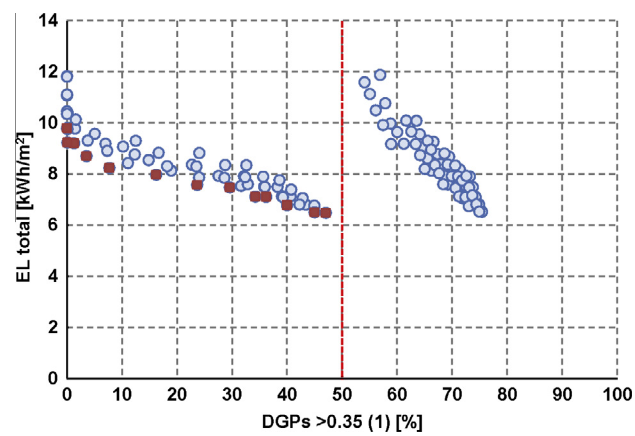

Fig. 6. Scatter plot of total annual lighting energy demand and $DGPs_{>0.35}$ at Point 1.

Note that the value of E_{Lmax} (100% utilisation) is around 25 kW h/m^2, hence both E_L and $DGPs_{>0.35}$ have the same scale on the graph.

At the WWR of 30% and 40%, the mean values of $UDI_{100-2000lx}$ are larger than the minimum criteria of 50%, indicating a sufficient amount of daylight. At somewhere between the WWR of 40% and 50%, both $UDI_{100-2000lx}$ and $DGPs_{>0.35}$ have a value of 50%. At larger WWR values, $DGP_{>0.35}$ is larger than 50%, giving the risk of glare and overheating during more than half of the occupied time.

On the relationship between wall reflectance and uniformity, it is observed that a higher wall reflectance results in a higher uniformity, in a linear way. Note that most studies on window optimisation assume a fixed value of wall reflectance, but it is shown here that wall reflectance also plays an important role. Compared to the minimum criterion of 0.2, it seems that almost all values of wall reflectance satisfy the requirement, except some half of the input combination with the wall reflectance of 0.4.

3.2. Multi-objective optimisation

The simulation results for all possible combinations are displayed in scatter plots in Figs. 6–11; each plot presents a pair of two contradicting performance indicators as defined in Section 2.2.3, and each dot on the graph represents a combination of the three input variables. The red lines denote the maximum or minimum criteria. The red dots represent combinations that fulfil the criteria and are located in the Pareto frontier.

Figs. 6–8 clearly shows two clusters of dots on the scatter plot; one cluster with $DGP_{s>0.35}$ of less than 50%, while other one has

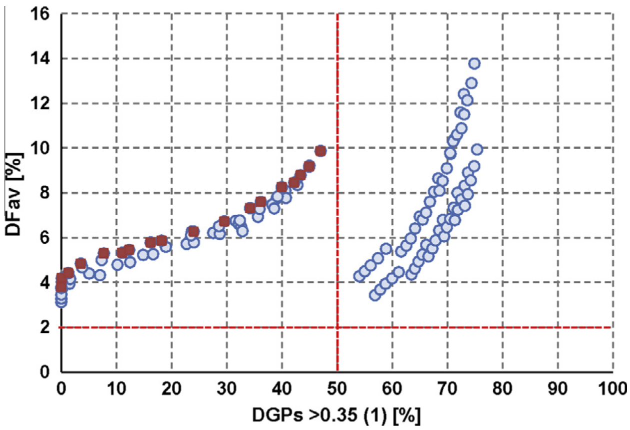

Fig. 7. Scatter plot of average DF and $DGPs_{>0.35}$ at Point 1.

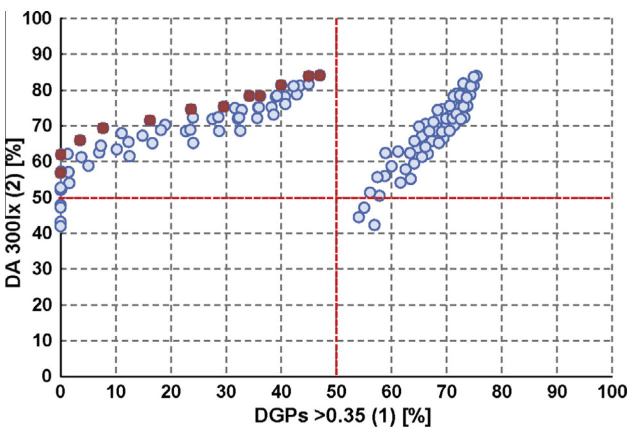

Fig. 8. Scatter plot of DA_{300lx} at Point 2 and $DGPs_{>0.35}$ at Point 1.

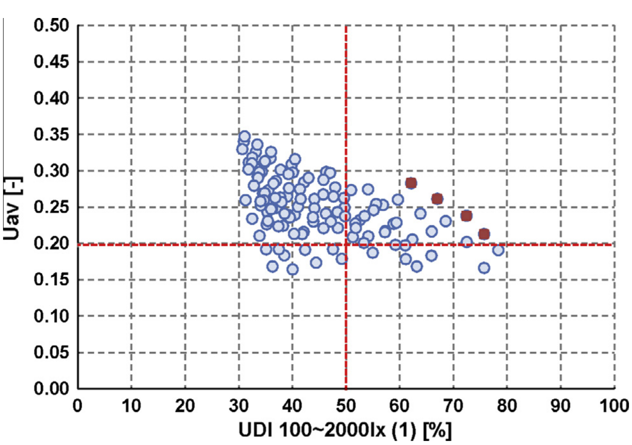

Fig. 9. Scatter plot of average uniformity and $UDI_{100–2000lx}$ at Point 1.

more than 50%. The former is the combinations with north or south window orientation, and the latter is those with east or west orientation, as briefly discussed in Section 3.1. Hence, no combinations with east or west orientation are selected as optimum solutions, since the requirement for $DGP_{s>0.35}$ is not satisfied.

Applying the optimisation criteria and algorithms (1) until (3) to filter the solutions, three optimum solutions are found. All of these solutions belong to exactly four Pareto frontiers; therefore they are ranked based on the mean distance to the utopia points,

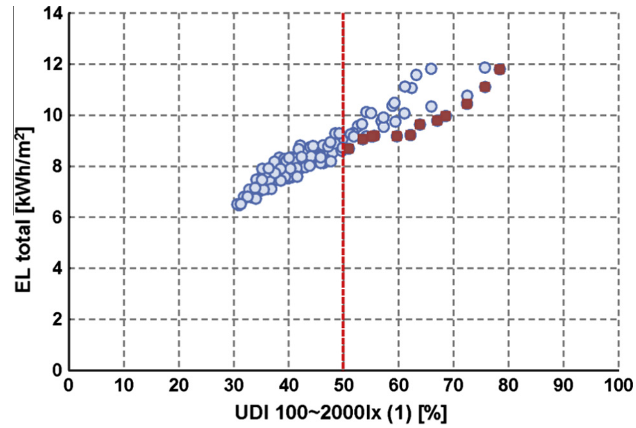

Fig. 10. Scatter plot of total annual lighting energy demand and $UDI_{100–2000lx}$ at Point 1.

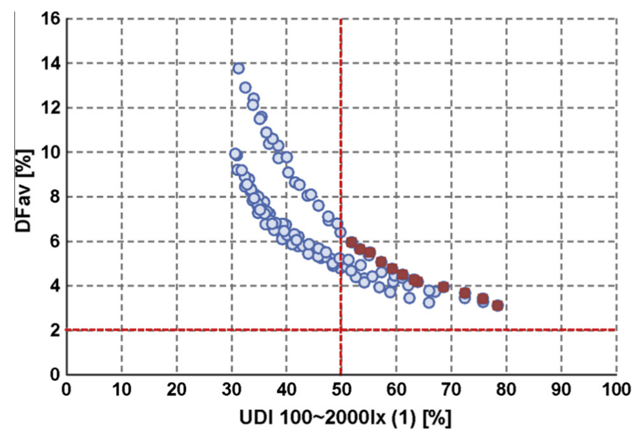

Fig. 11. Scatter plot of average DF and $UDI_{100–2000lx}$ at Point 1.

as listed in Table 2. Wall reflectance is written as ρ_w, and window orientation is given in degrees (0° is North, 90° is East, and so forth).

Based on the mean distance to the utopia point, the combination of 30% WWR, 0.8 wall reflectance, and south window orientation is the most optimum solution. Table 2 also shows that a small WWR, 30% in this case, is the most plausible option to achieve a balanced performance of lighting energy demand and visual aspect. This is in parallel with other studies of windows and façade design in the tropics (e.g. [52]). High values of wall reflectance (0.7–0.8) appear in the tables as they are responsible for creating a more uniform light distribution on the workplane.

South window orientation appears in all of the three optimum solutions. Note that the north façade, which faces the equator (as Bandung is located at latitude 6.93°S), receives a large amount of solar radiation in the mid-year, when the sun's apparent position is due north and the precipitation is low (dry season). Hence, in view of a north–south orientation, which is traditionally preferred over an east–west orientation, a south-facing window is likely to give a better performance rather than the north-facing one.

It is also noted that no solutions actually belong to the Pareto frontier in all of the six pairs, showing that it is practically impossible to fulfil all defined performance criteria at all time. For example, the combination of 30% WWR, 0.8 wall reflectance, and south window orientation (i.e. the most optimum solution in Table 2) is not a non-dominated solution in the pairs of DF_{av} vs $DGP_{>0.35\ (1)}$ and DF_{av} vs $UDI_{100–2000lx\ (1)}$. Even though this optimum solution fail

Table 2
List of the optimum solutions based on the mean distance (d_{av}) to the utopia points.

d_{av} (%)	WWR (%)	ρ_w (−)	Orient. (°)	DF_{av} (%)	U_{av} (−)	$DA_{300\ (2)}$ (%)	$UDI_{100-2000\ (1)}$ (%)	$DGPs_{>0.35\ (1)}$ (%)	E_L (kW h/m^2)
52.4	30	0.8	180	4.0	0.28	62.0	62.2	0.1	9.2
56.3	40	0.7	180	4.8	0.27	65.9	51.0	3.6	8.7
62.2	30	0.7	180	3.7	0.26	56.9	67.1	0.0	9.8

to become non-dominated solutions in those mentioned pairs, it is actually located near the Pareto frontiers anyway. Furthermore, since there is no common pairs in which both optimum solutions do not belong to the Pareto frontiers, one cannot simply remove any pair from the observation. This echoes the statement in the Introduction, noting that the quest for the most appropriate daylight metrics is still far from finish. For the time being, it is arguably still necessary to consider all daylight metrics as a whole, when performing optimisation for windows and façade orientation.

As mentioned in Section 2.2.3, graphical optimisation method was applied in this study, since it is the most direct way to observe the inter-relationship between the involved metrics or performance indicators. Furthermore, it also provides a possibility to visualise the boundaries of the solution space, which in most cases will significantly reduce the complexity of the problem. Once the boundaries of the solution space has been determined, the design team has options to choose from any conflicting objectives (e.g. visual comfort and energy consumption), in order to reach a compromise between project expectations and final design [30].

The algorithm proposed in this study also points out the necessity for designers to decide beforehand the number of relevant metrics (or performance indicators) and their criteria, which are to be satisfied. In reality, it is practically impossible to satisfy all criteria, but a minimum proportion of satisfied criteria must be achieved anyway. This study provides a worked example on how to proceed when some of the defined criteria are not satisfied, and how to rank the possible optimum solutions. It should be noted again that the focus is to demonstrate the role of criteria consideration in optimising the design variables, while observing the inter-relationship between the performance indicators, rather than to find the exact global optimum solution. The simplified optimisation problem presented in this study is essentially a 'proof of concept' of the idea that considering multiple criteria to limit the solution space can in turn yield reasonable solutions.

4. Conclusion

A simple design optimisation approach is proposed in this study to investigate the most optimum combination of window-to-wall ratio, wall reflectance, and window orientation for buildings in the tropics. Sensitivity analysis was applied to observe the general tendency of relationship between the input and output variables. To find the optimum solutions, results were grouped by pairing two different performance indicators with conflicting trend that requires a trade-off. A certain procedure is proposed to filter the solutions: (1) applying the relevant optimisation criteria to the Pareto frontiers in all pairs, (2) accepting the filtered Pareto frontiers in all pairs into the optimum solution space if they belong to the Pareto frontier in at least 4 out of 6 pairs of performance indicators, and (3) ranking the sorted optimum solutions in the order of their mean distance to the utopia points, or in the order of number of times they belong to a Pareto frontier. The mean distance to the utopia points is preferred over the number of belonging to a Pareto frontier.

Three optimum solutions are found, all of which belong to four Pareto frontiers. The most optimum solution with the least mean distance to the utopia points is the combination of WWR 30%, wall reflectance of 0.8, and south orientation. Despite the simplified approach and limited number of performance indicators, the graphical optimisation method in this study enables one to directly observe the inter-relationship between the involved performance indicators. The proposed method also provides a possibility to visualise the boundaries of the solution space, which in most cases will significantly reduce the complexity of the problem.

It is however noted that more complex situations, for instance in the presence of additional building elements and shadings, may result in different optimum solutions. Different window configurations, though having the same WWR, can lead to a different energy and daylight performance as well. Additional comfort aspects, such as on thermal and acoustics, may also shift the criteria into a more compromised setpoint. Even the criteria on visual aspect itself can be further improved by considering a more accurate glare index, a relevant descriptor for pleasantness of the outside view, and many more. Despite the limitations, this study can serve as a starting point in helping building designers to optimise building performance in a simple approach.

Acknowledgements

This work is a part of research funded by the Institute of Research and Community Service of Institut Teknologi Bandung (LPPM ITB), under the contract number 0217i/I1.C06/KP/2015.

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